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(54) Title: DEVICES AND METHODS FOR LOCATING DEFECTIVE FILTER ELEMENTS AMONG A PLURALITY OF FILTER ELEMENTS

(57) Abstract

The present invention includes a device for locating defective filter elements among a plurality of filter elements. The device includes a sound monitoring apparatus and a processing circuit. The sound monitoring apparatus is associated with a plurality of filter elements to detect sounds emanating from the plurality of filter elements and produce output signals indicative of the sounds. The processing circuit is coupled to the sound monitoring apparatus to determine the location of defective filter elements among the plurality of filter elements based on the output signals. The present invention also includes a probe for locating defective filter elements based on sounds emanating from the filter elements.

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Devices and Methods for Locating Defective Filter Elements Among a Plurality of Filter Elements

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to devices and methods for locating defective filter elements among a plurality of filter elements. More particularly, the present invention relates to devices and methods for locating defective filter elements by monitoring sounds emanating from defective filter elements.

2. Discussion of the Related Art

Filter assemblies used in industrial applications may include more than one filter element to filter a fluid. For example, some filter assemblies may include as many as 500 or more filter elements arranged in parallel to filter a fluid. One or more of the filter elements in a filter assembly may include or develop a defect such as a hole or tear that permits fluid to bypass the defective filter element. As a result, the performance of the entire assembly may be adversely affected. One conventional method for improving performance of a filter assembly is replacing all of the filter elements in the filter assembly. However, in order to reduce waste, locating and replacing only the defective filter element or elements is desirable, particularly in filter assemblies with large numbers of filter elements.

Locating defective filter elements among large numbers of filter elements may be time consuming. One conventional method for locating a defective filter element among a plurality of filter elements consists of wetting all of the filter elements in a filter assembly with a wetting solution, subjecting the filter elements to a gas pressure, monitoring the bulk gas flow rate through the filter assembly, and comparing the bulk gas flow rate to a predetermined range of flow rates. If the flow rate exceeds the predetermined range, one or more of the filter elements is determined to be defective.

When one or more of the filter elements is determined to be defective, the filter elements are individually replaced on a trial and error basis and the test is repeated until all of the defective filter elements are removed. Many non-defective filter elements may be replaced and many iterations of the test may be performed before locating the defective filter element. Thus, this conventional method for locating a defective filter element is time consuming and labor intensive.

Another conventional method for locating a defective filter element among a plurality of filter elements consists of isolating groups of more than one filter element to determine whether a group contains a defective filter element. More particularly, all of the filter elements in a filter assembly are wetted and subjected to a gas pressure. Next, the bulk gas flow rate is measured and compared to a predetermined range. If the flow rate exceeds the predetermined range, a group of filter elements is isolated from the remainder of the filter elements. The remainder of the filter elements are then subjected to gas pressure. The gas flow rate is compared to a second predetermined range. If the gas flow rate exceeds the second predetermined range, a second group is isolated and the test is repeated. If the gas flow rate does not exceed the second predetermined range, the isolated group may contain one or more defective filter elements. The filter elements in the isolated group are then individually tested for defects.

Isolating groups of filter elements after the initial bulk test reduces the time required to locate a defective filter element in comparison with the previously described method where filter elements are individually replaced by trial and error. However, a significant amount of hardware, such as a plurality of conduits, valves, and outlet headers, may be required for each group of filter elements. Such hardware adds to the cost and complexity of filter assemblies. Accordingly, there exists a need for devices and methods for quickly and accurately locating defective filter elements among a plurality of filter elements without extensive hardware.

SUMMARY OF THE INVENTION

The present invention avoids at least some of the difficulties associated with conventional methods for locating defective filter elements among a plurality of filter elements.

According to one aspect of the invention, a device for locating defective filter elements among a plurality of filter elements includes a sound monitoring apparatus associated with a plurality of filter elements to detect sounds caused by one or more defects in the plurality of filter elements and produce output signals indicative of the sounds. A processing circuit is coupled to the sound monitoring apparatus to determine the location of defective filter elements among the plurality of filter elements based on the output signals.

According to another aspect of the invention, a filter assembly includes a housing, a plurality of filter elements located in the housing, and a sound monitoring apparatus associated with the filter elements to detect sounds caused by one or more defects in the filter elements. A processing circuit is coupled to the sound monitoring apparatus to determine the location of defective filter elements based on the output signals.

According to another aspect of the invention, a probe for locating defective filter elements among a plurality of filter elements includes a plug removably couplable to a filter element to allow a predetermined pressure to be applied to the filter element. A microphone is cooperatively arranged with the plug to detect sounds indicative of a defect in the filter element. A processing circuit is coupled to the microphone to indicate defective filter elements based on the sounds.

According to another aspect of the invention, a method for locating a defective filter element among a plurality of filter elements includes forcing gas through defective filter elements among a plurality of filter elements. The method also includes detecting sounds caused by the gas and determining the location of a defective filter element based on the sounds.

According to another aspect of the invention, a method for locating defective filter stacks or elements among a plurality of filter stacks or elements includes controlling a liquid level inside a filter housing with respect to a plurality of filter stacks or filter elements. Gas pressure is applied to the filter stacks or the filter elements. Sounds caused by bubbles originating from defective filter stacks or filter elements are monitored to locate defective filter stacks or elements.

According to another aspect of the invention, a method for locating defective filter elements includes transmitting acoustic energy within a filter housing. Acoustic energy reflected or transmitted within the housing is monitored to locate defective filter elements.

According to another aspect of the invention, a system for locating a defective filter element among a plurality of filter elements includes a pressure control arrangement associated with a filter housing for forcing gas through defective filter elements among a plurality of filter elements inside the filter housing. At least one sound monitoring apparatus is associated with the filter housing for detecting sounds caused by the gas. A processing circuit is coupled to the sound monitoring apparatus for determining the location of a defective filter element based on the sounds.

According to another aspect of the invention, a system for locating defective filter stacks or elements among a plurality of filter stacks or elements includes a liquid level control device associated with a filter housing for controlling a liquid level inside a filter housing with respect to a plurality of filter stacks or filter elements a pressure control arrangement is associated with the filter housing for applying gas pressure to the filter stacks or the filter elements. A sound monitoring apparatus is associated with the filter housing for monitoring sounds caused by bubbles originating from defective filter stacks or filter elements. A processing circuit is coupled to the sound monitoring apparatus for indicating the presence or absence of sounds caused by the bubbles.

According to another aspect of the invention, a system for locating defective

filter elements includes a transducer for transmitting acoustic energy within a filter housing. At least one sound monitoring apparatus monitors acoustic energy reflected or transmitted within the housing. A processing circuit processing circuit is coupled to the sound monitoring apparatus and the sound transducer for locating defective filter elements based on the monitored acoustic energy.

An advantage of the devices and methods according to the present invention is that they are capable of quickly and accurately locating defective filter elements or modules among a plurality of filter elements.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a device for locating defective filter elements according to an embodiment of the present invention.

Figure 2 is a device for locating defective filter elements according to the embodiment of Figure 1.

Figure 2a is a top view of a filter housing and a plurality of microphones according to the embodiment of Figure 2.

Figure 3 is a flow chart of a method for locating defective filter elements according to an embodiment of the present invention.

Figures 3a-3c are timing diagrams of output signals from the microphones M1 through M3 illustrated in Figure 2a.

Figure 4 is a top view of a filter housing including a first set of possible locations for defective filter elements relative to microphones M1 and M3.

Figure 5 is a top view of a filter housing including a second set of possible locations for defective filter elements relative to microphones M2 and M3.

Figure 6 is a top view of a filter housing and the intersection of the first and second sets of potential locations for defective filter elements.

Figure 7 is a block diagram of a probe for locating defective filter elements.

Figure 8 is a sectional view of a probe for locating defective filter elements according to the embodiment of Figure 7.

Figure 9 is a side view of a probe for locating defective filter elements according to another embodiment of the present invention.

Figure 10 is a sectional view of a filter assembly including a plurality of stacked filter elements in which embodiments of the present invention may be used to locate defective filter elements.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 illustrates a device for locating defective filter elements among a

plurality of filter elements according to an embodiment of the present invention. The device preferably includes a processing circuit 2, a sound monitoring apparatus 4, and a pressure control arrangement 6. A filter assembly 8 comprises a housing including a plurality of filter elements. The processing circuit 2, the sound monitoring apparatus 4, and the pressure control arrangement 6 cooperate to rapidly and conveniently locate one or more defective filter elements in the filter assembly 8 by determining the source of sounds caused by the defective filter elements.

The pressure control arrangement 6 comprises any device suitable for regulating pressure in the filter assembly. For example, the pressure control arrangement may comprise a source of compressed gas, or pump, e.g., a gas pump, for pressurizing the filter assembly. One or more conduits 10 couple the pressure control arrangement to the filter assembly 8.

The pressure control arrangement 6 regulates the pressure in the filter assembly 8 to cause defective filter elements in the filter assembly 8 to produce sounds above the background noise level in the filter assembly. For example, in one test, the filter elements in the filter assembly 8 are wetted with a wetting solution, such as water or an alcohol. First and second regions of the filter assembly on opposite sides of the filter elements, e.g., upstream and downstream regions, downstream and upstream regions, lower and upper regions, or upper and lower regions, are filled with a gas, such as air. The pressure control arrangement 6 increases the pressure differential between the first and second regions to a predetermined test pressure, e.g., to or just below the anticipated bubble point of the filter elements. Sounds caused by gas passing through a defect in a filter element, such as a hole, an oversized pore, or a tear, may be used to locate one or more defective filter elements among the plurality of filter elements.

In another test, either the upstream or downstream side of the plurality of filter elements may be submerged in a liquid. The pressure control arrangement increases pressure on the side of the filter elements that is not submerged in a liquid

to a predetermined test pressure, e.g., to the anticipated bubble point. Gas passing through defects in one or more filter elements produces bubbles in the liquid. The bubbles rise and burst at the surface of the liquid. Sounds caused by the forming, rising, or bursting of gas bubbles may be used to locate a defective filter element.

The device for locating defective filter elements according to the illustrated embodiments is not limited to any particular test for causing defective filter elements to produce sounds above the background noise level in the relevant system. United States Patent No. 5,576,680, issued November 19, 1996, to Hopkins et al. (hereinafter, "Hopkins"), the disclosure of which is incorporated herein by reference, discloses a plurality of tests for applying pressure to and identifying whether a filter element is defective based on sound. For example, Hopkins discloses that pressure may be ramped or stepped upwards to the anticipated bubble point to test the integrity of a filter element. Any test for pressurizing a filter element to cause the filter element to emanate sounds if defective is within the scope of the invention.

Although the illustrated embodiment depicts the pressure control arrangement 6 as being coupled to the processing circuit 2, the present invention is not limited to such an embodiment. For example, the pressure control arrangement 6 may be a separate device having its own processing circuitry to regulate pressure in the filter assembly 8. Either arrangement for controlling the pressure in the filter assembly 8 is within the scope of the invention.

The sound monitoring apparatus 4 comprises any device suitable for monitoring sounds emanating from defective filter elements to enable the source of the sounds to be located. These sounds may be primary sounds or secondary sounds, such as sounds reflected within the filter housing. For example, the sound monitoring apparatus may comprise one or more microphones positioned at various locations near, preferably inside, the filter assembly 8 to monitor the sounds emanating from defective filter elements. The microphones are preferably corrosion resistant to their operating environment. For example, in embodiments where the

microphones are submerged in a liquid, the microphones may comprise stainless steel.

In order to detect sounds indicative of defects, the microphones are preferably capable of detecting acoustic frequencies corresponding to acoustic frequencies of sounds emanating from defective filter elements. For example, where sounds emanating from defective filter elements are in the ultrasonic range, the microphones are preferably capable of detecting ultrasonic frequencies. However, the present invention is not limited to monitoring any particular acoustic frequency range. Monitoring any acoustic frequency range that includes sounds indicative of a defect is within the scope of the invention.

In addition, the microphones preferably include rise time characteristics tailored to the method for locating defective filter elements. For example, in some embodiments, the difference in time of detection or arrival of an acoustic signal at various microphones may be used to locate defective filter elements. In such embodiments, the microphones preferably have a short rise time in comparison with the time difference between time of arrival or detection of the sound by the microphones, so that the differences in time of arrival of acoustic signals may be accurately determined.

The processing circuit 2 comprises any circuit capable of indicating the source of a sound based on the signal or signals output from the sound monitoring apparatus 4. For example, the processing circuit 2 may comprise a microprocessor or microcontroller and software for analyzing the signals output from the sound monitoring apparatus 4 to locate defective filter elements. The processing circuit analyzes characteristics of the electrical signals output from the sound monitoring apparatus, such as magnitude, phase, frequency, and/or time delay, to locate defective filter elements. The present invention is not limited to using a microprocessor and software to locate defective filter elements. Any analog or digital circuitry that is capable of indicating the source of a sound is within the scope of the invention.

Figure 2 illustrates one example of a device for locating defective filter elements according to the embodiment of Figure 1. In the illustrated embodiment, the filter assembly 8 comprises a housing 20 including a plurality of filter elements 22 suspended from a top-mounted tube sheet 24. Where the direction of flow during the filtration phase of operation is outside-in through the filter elements 22, the filter elements 22 and the tube sheet 24 divide the interior region of the housing into an upstream region 26 below the tube sheet 24 and a downstream region 28, generally above the tube sheet 24 and in the interior of the filter elements 22. The filter elements 22 are coupled to apertures 30 in the tube sheet 24. The filter assembly also includes a fluid inlet 32 and a fluid outlet 34. In operation, fluid flows through the inlet 32, to the upstream region 26, through the filter elements 22, through the apertures 30, into the downstream region 28, and through the outlet 34. A wide variety of other ports may be located in the housing, including drainage ports and ports for backwash or blowback operations.

The present invention is not limited to locating defective filter elements in filter assemblies where the tube sheet is a top-mounted tube sheet and/or the flow is outside-in through the filter elements. The present invention may also be used to locate defective filter elements where the tube sheet is a bottom-mounted tube sheet and/or the flow is inside-out through the filter elements. For example, an inside-out flow filter assembly may comprise a housing, a top-mounted tube sheet in an upper portion of the housing, and a plurality of filter elements extending downward from the tube sheet, similar to the filter assembly 8 of Figure 2. However, unlike the filter assembly 8 of Figure 2, fluid may enter the filter housing through an inlet above the tube sheet, flow through the interiors of the filter elements, through the filter media of the filter elements, and exit the housing through an outlet below the tube sheet. In such an embodiment, the upper portion comprises the upstream region and the lower portion comprises the downstream region.

The present invention is not limited to use with the filter assembly 8 illustrated

in Figure 2. Embodiments of the present invention may be used to locate defective filter elements in any type of filter assembly for filtering fluids, including liquids and gases. For example, embodiments of the present invention may be used to locate defective filter elements in a stacked filter assembly wherein a plurality of disk-shaped filter elements are axially spaced along a central conduit or in a filter module wherein a plurality of stacked filter units communicate with inlet, outlet, and permeate conduits. Other filter assembly configurations in which the embodiments of the present invention may be used include cross flow filters, horizontally disposed filters, and bottom-mounted tube sheet filters with standing filter elements.

The sound monitoring apparatus 4 preferably comprises a plurality of microphones located inside the filter housing 20. In the illustrated embodiment, three microphones M1-M3 are located in the downstream region 28 of the filter housing 20. However, the present invention is not limited to such a configuration. For example, the microphones may be located in the upstream region 26, in both the upstream and downstream regions of the filter housing 20, or in conduits coupled to either region.

The microphones may be coupled to the filter elements through any medium capable of communicating sound between the filter elements and the microphones M1-M3. For example, medium between the microphones and the filter elements may be a solid, a liquid, a gas, or any combination of solids, liquids, and gases.

Figure 2a illustrates an exemplary spacing of the microphone M1-M3 in the downstream region 28 of the filter housing 20. The microphones M1-M3 are spaced 120° apart along the perimeter of the filter housing 20. Spacing the microphones M1-M3 as illustrated provides suitable coverage for a cylindrical filter housing using three microphones. However, any spacing of the microphones that allows location of defective filter elements is within the scope of the invention.

Although the illustrated embodiment includes three microphones M1-M3, any number of microphones is within the scope of the invention. The number of

microphones used depends many factors, including the geometry of the filter assembly, the processing algorithm used to locate defective filter element, cost considerations, and the desired accuracy of the device. Increasing the number of microphones may increase the accuracy of the device; however, increasing the number of microphones may increase cost. If microphones can be obtained relatively inexpensively, it may be desirable associate a microphone with each filter element in the filter assembly. In such an embodiment, the processing circuit 2 may locate defective filter elements simply by determining the microphone that first detects a signal caused by a defect or, alternatively, the microphone having the highest output signal intensity. Alternatively, a microphone may be associated with a subgroup of filter elements, e.g., a subgroup of 5-20 filter elements. In such an embodiment, the processing circuit may locate defective filter elements simply by isolating a defective filter element as being within a specific subgroup of filter elements. A probe may be used to locate the defective filter element within a subgroup, as will be discussed below.

In yet another alternative embodiment, a single microphone or two or more microphones may be automatically or manually movable within the filter housing 20. In such an embodiment, the microphone may be movable to different axial and/or radial positions inside the filter assembly 20 to monitor sounds emanating from defective filter elements. The processing circuit may utilize signals recorded at the various positions to locate defective filter elements.

Referring back to Figure 2, the processing circuit 2 is coupled to the microphones M1-M3 through a communication link 42. The communication link 42 comprises one or more electrical conductors, optical fibers, or other signal transmission media coupled to the microphones M1-M3. The processing circuit preferably includes signal conditioning circuitry 60, e.g., amplifiers, filters, A/D converters, to condition and sample the signals output from the microphones for further processing. A memory 62 may be used to store the signals output from the

signal conditioning circuitry and programs for locating defective filter elements. The memory may also store programs for controlling the pressure control arrangement 6. A microprocessor 63 processes data according to the programs and controls input/output functions. The processing circuit may also include a display 64 to indicate the location of defective filter elements to an operator. An operator interface 66, such as a keyboard, may be included to allow the operator to control the operation of the device.

The pressure control arrangement 6 may comprise a pump and at least one valve for regulating the output from the pump. In a preferred embodiment, the pressure control arrangement comprises a gas pump, e.g., an air pump. The pressure control arrangement 6 is coupled to the upstream and downstream sides of the filter assembly 8 through conduits 10, 12, respectively. In an alternative embodiment, the pressure control arrangement 6 may be coupled to either the upstream or downstream side of the filter assembly 8.

The device of Figure 2 may locate defective filter elements in the filter assembly 8 using a variety of methods. For example, the filter elements may be wetted, the pressure control arrangement may increase the differential pressure between the upstream and downstream regions in the filter assembly. The microphones may monitor sounds emanating from defective filter elements. The processing circuit may locate defective filter elements based on the sounds. In another test, either the upstream region or the downstream region may be partially or completely filled with a liquid. The pressure control arrangement may increase the differential pressure between the upstream and downstream regions, and the microphones may monitor sounds caused by the rising, formation, and/or bursting of bubbles in the liquid.

Figure 3 illustrates a flow chart of an exemplary method for locating defective filter elements utilizing the device illustrated in Figure 2. First, the filter housing 20 is preferably closed to reduce background noise and to allow pressurization in the

upstream and/or downstream regions. Next, the downstream region 28 of the filter housing is partially filled with a liquid 50, such as water or filtrate. For example, the quantity of liquid in the downstream region 28 may range from a quantity sufficient to fill the cores of the filter elements 22 to a quantity sufficient to nearly fill the downstream region 28, while leaving an air gap for bursting of bubbles. In order to provide liquid to the downstream region a liquid source may be connected to the conduit 12 of the filter assembly. Alternatively, the liquid may be added to the downstream region 28 before the filter housing 20 is closed using any suitable means. In yet another alternative, filtrate present in the downstream region 28 may be used as the liquid during testing. The liquid 50 preferably fills the cores of the filter elements 22 and wets the filter medium of each of the filter elements 22. The microphones M1-M3 are activated, preferably after the liquid fills the cores, to continuously monitor sounds emanating from the filter elements 22. The conditioning circuitry 6 amplifies, filters, samples, and/or digitizes the signals output from the microphones M1-M3. The sampling rate is preferably chosen to satisfy the Nyquist criterion, based on the highest frequency in the signals output from the microphones. For example, if the highest output frequency is 100 kHz, the sampling rate is preferably at least about 200 kHz and most preferably at least about 500 kHz. The memory 62 records the signals output from the microphones M1-M3 in real time, such that at any given instant of time, the memory contains a "snapshot" of the output signals from the microphones M1-M3.

Once the microphones are activated, the pressure control arrangement 6 increases the pressure in the upstream region 26 of the filter housing, which is preferably drained of any liquid. In a preferred embodiment, the pressure control arrangement 6 ramps or steps the pressure slowly upward to reduce the likelihood of detecting multiple defects simultaneously. The pressure may be slowly increased to a value at or just below the anticipated bubble point of the filter elements. The processing circuit analyzes the signals output from the microphones to determine

whether a defect is present. For example, if one of the filter elements 22 is defective, air may pass through the defect and form a bubble stream 52 in the liquid 50. The bubbles in the bubble stream 52 rise in the liquid 50, through the core of the defective filter elements, and burst at the surface of the liquid. The bursting of bubbles creates acoustic signals. The acoustic signal caused by each bubble may cause the amplitude of the signal output from the microphones to be greater than a predetermined threshold, or the acoustic signals caused by the series of bubbles may have a characteristic signature. The processing circuit may determine whether a defect is present by comparing the amplitude to the predetermined threshold or by identifying the signature as one indicative of a defective filter element. If a predetermined test pressure, e.g., the anticipated bubble point of the filter elements, is reached without detection of any defects, the processing circuit may determine that the filter assembly is non-defective. The processing circuit may then indicate that the test was passed, e.g., on the display 64.

When the processing circuit determines the presence of a defect, the processing circuit preferably calculates the location of the defective filter element based on the output signals. In one embodiment, the processing circuit calculates the location of defective filter elements based on the relative time of detection of the acoustic signal caused by the defect by each of the microphones M1-M3. For example, the microphones M1-M3 may detect the acoustic signal at time periods indicative of the distance between each microphone and the bubble stream 52. Each microphone transmits an electrical signal to the processing circuit. The processing circuit conditions and samples the output signals. Signals S1-S3 in Figures 3a-3c, represent exemplary signals output from the microphones M1-M3, after conditioning and sampling. The high portions of the signals may represent the bursting of a bubble at the surface of the liquid 52. The low portions of the signals may represent the time period between the bursting of bubbles. The memory 62 stores values indicative of the signals S1-S3 in real time.

When at least one bubble has been detected by each of the microphones, the processing circuit 2 utilizes a signal processing algorithm to determine the relative time of detection of the acoustic signals caused by the bubbles. For example, the processing circuit may utilize a cross-correlation algorithm to "slide" the signals S1-S3 in time relative to each other until the signals match. The amount of time that one signal moves relative to another until a match occurs represents the difference between the times of arrival of the acoustic signal caused by the bubbles at two of the microphones. In the illustrated embodiment, t_{31} represents the difference between times of arrival of the acoustic signal at the microphone M3 and the microphone M1 and t_{32} represents the difference between times of arrival at the microphone M3 and the microphone M2.

Although the signals S1-S3 in Figures 3a-3c each indicate two bubbles or high pulses, the present invention is not limited to determining the relative time of detection of a defect using two high pulses. For example, the cross-correlation algorithm may be performed after each of the microphones M1-M3 detects a single bubble. However, since the signals are cross correlated based on comparison of high and low portions, the more data collected by the microphones, the more accurate the calculation. Thus, the processing circuit may wait until the microphones have each detected a predetermined number of bubbles before determining the relative time of arrival of the signals.

After the processing circuit determines the relative times of arrival of the acoustic signal at the microphones M1-M3, the processing circuit determines the relative distances of the microphones M1-M3 from the bubble stream 52. For example, referring to Figure 2a, the distances d_1, d_2, and d_3 represent the distance of the defect from each of the microphones M1, M2, and M3. The processing circuit uses the differences between the arrival times of the acoustic signal at each of the microphones to determine the difference between the distances d_1, d_2, and d_3. For example, the processing circuit may use the time t_{31} and the speed of sound in the

medium to determine the difference between d_3 and d_1. Similarly, the processing circuit may use the speed of sound in the medium and the time t_{32} to determine the difference between the distances d_3 and d_2.

In order to calculate the differences between the distances, the processing circuit multiplies the time differences by the speed of sound in the medium. For example, in Figure 2a, the medium between the microphones and the surface of the liquid is air, and the speed of sound in air is about 343 m/s at 20°C. Accordingly, the processing circuit calculates the difference between d_3 and d_1 by multiplying t_{31} by 343 m/s. The processing circuit performs a similar calculation to determine the difference between d_3 and d_2. The present invention is not limited to measuring distance at any particular temperature or in any particular medium. The device may further comprise a temperature sensor to sense the temperature inside the filter housing. The processing circuit may include temperature compensation algorithms to account for changes in sound velocity due to temperature changes in the medium and store sound velocity constants for media other than air.

After the processing circuit calculates the differences between the distances, the processing circuit preferably determines potential locations for the defective filter element relative to the microphones. The processing circuit may utilize any one of a variety of geometric algorithms to determine the potential locations. For example, in one method, the processing circuit determines a first set of potential locations relative to microphones M1 and M3 and a second set of potential locations relative to the microphone M2 and M3. The processing circuit then uses the intersection of the sets to locate the defective filter element.

Figure 4 illustrates potential locations of the defective filter element based on the difference in time of arrival of the acoustic signal caused by the defect at microphones M1 and M3. Each of the hyperbolic curves H_0-H_n represents a locus of points such that the differences in the distances from the points on the curve to the microphones M1 and M3 is constant. Thus, one of the hyperbolic curves represents a

set of potential locations of the defective filter element. For example, the processing circuit may determine that microphone M1 is closer to the sound source than M3 by a constant difference, calculated based on the time difference t_{31}, as explained above. The curve H_1 may represent the first set of potential locations for the defective filter element based on t_{31}. The processing circuit preferably ignores points that are outside of the filter housing 20, since the defective filter element is within the filter housing 20. If there is only one filter element actually located in the first set of potential locations, the processing circuit may determine that the defective filter element has been located. If there are a plurality of filter elements in the first set of potential locations, the processing circuit may calculate another set of potential locations, for example, using the microphones M2 and M3.

Figure 5 illustrates potential locations of the defective filter element based on the difference in time of arrival of the acoustic signal caused by the defect at microphones M2 and M3. Each of curves I_o-I_n represents a locus of points, such that the difference in the distances from the points on the curve to the microphones M2 and M3 is constant. For example, the processing circuit may determine that M2 is closer to the sound source than M3 by a constant difference, calculated based on the time difference t_{32}, as explained above. The curve I_1 may represent the second set of potential locations for the defective filter element based on t_{32}.

If the second set of potential locations represented by the curve I_1 in Figure 5 intersects the first set of potential locations represented by the curve H_1 in Figure 4, and one filter element lies at the intersection, the processing circuit determines that the defective filter element lies at the intersection. The point L_1 in Figure 6 illustrates the intersection of the curves H_1 and I_1 and the potential location of the filter element. If the sets do not intersect or if the intersection encompasses more than one filter element, the processing circuit may determine more potential locations and determine more intersections until the defective filter element is located to a desired degree of certainty.

The location determined by the processing circuit may be exact or approximate. For example, in some embodiments, the processing circuit may identify a specific filter element suspected of being defective using the method described above. Alternatively, the processing circuit may determine a region in a filter assembly in which one or more filter elements may be defective. In such an embodiment, the specific locations of defective filter elements may be determined using a probe device, as will be described below.

After the processing circuit determines the location of a defective filter element, the processing circuit preferably indicates the location of the defective filter element to the operator. For example, the processing circuit may display the location of the defective filter element on the display 64, illustrated in Figure 2. In embodiments in which the display has graphics capability, the processing circuit may display a top view of all of the filter elements in the filter assembly and highlight those elements that are potentially defective. If the display does not have graphics capability, defective filter elements may be indicated in any appropriate manner, such as coordinates or numbers.

After the processing circuit determines the location of a defective filter element, the pressure control arrangement preferably continues to increase the pressure in the filter housing to the predetermined test pressure. The processing circuit preferably filters out or ignores signals caused by defective filter elements for which locations have already been calculated. The processing circuit locates any additional defective filter elements using the method described above. In this manner, the device is capable of detecting multiple defective filter elements during one iteration of the test, without requiring the reopening of the housing or the replacement of previously-located defective filter elements. Conventional methods for locating defective filter elements require repeated replacement of filter elements and retesting to locate defective filter elements. Thus, the device according to the present embodiment saves time and labor, as compared with conventional methods for

locating defective filter elements.

After the maximum test pressure is reached, and the processing circuit 4 has determined the location of one or more defective filter elements, the filter housing 20 is preferably opened. Defective filter elements may be replaced based on the calculated locations without further testing. However, because the calculated locations may be approximate, the specific locations of defective filter elements may be verified or determined using a probe for locating defective filter elements according to another aspect of the invention.

Figure 7 illustrates a block diagram of a probe 100 for locating defective filter elements. The probe 100 comprises a microphone M4. A coupling device 124, e.g., an electrical connector, connects the microphone M4 to a processing circuit, for example, as illustrated in Figure 2. Alternatively, the probe 100 may include internal processing circuitry for analyzing the output signals from the microphone M4. The probe 100 may also include a pressure line 104 for coupling the probe to a pressure control arrangement, for example, as illustrated in Figure 2. The pressure line allows the probe 100 to individually apply pressure, i.e., a positive or negative pressure, to filter elements in order to locate defective filter elements without the hardware associated with conventional pressure control arrangements. In an alternative embodiment, the pressure line 104 and the plug 102 may be omitted, and the probe 100 may comprise one or more microphones. Such a probe may be used as a portable sound monitoring device for locating defective filter elements when the filter elements are pressurized using external devices.

Figure 8 illustrates one example of a probe 100 for locating defective filter elements according the embodiment of Figure 7. The probe 100 comprises a plug 102, a microphone M4, and a pressure line 104. The plug 102 is preferably capable of coupling with an aperture in the tube sheet 24 or an open end cap 106 of a filter element 22 so that pressure may be applied to the filter element 22. In the illustrated embodiment, the plug 102 is insertable into the open end cap 106 of the filter element

22. To facilitate insertion into the open end cap 106, the probe 102 includes a beveled outer surface 108. In an alternative embodiment, the probe 100 may be capable of coupling with the filter element 22 to allow pressure to be applied to the filter element without being inserted into the open end cap 106. For example, the plug 102 may comprise a covering member capable of covering the aperture in the tube sheet 24 or end cap 106 of the filter element 22. However, in a preferred embodiment, the plug 102 is insertable into the filter element 22 to facilitate coupling. In a most preferred embodiment, an end 110 of the plug 102 abuts against the core 112 of the filter element 22.

The plug 102 may comprise any material capable of coupling with the filter element 22 to allow pressure to be applied to the filter element. For example, in some embodiments, the plug 102 may comprise a resilient material, e.g., Buna rubber. In alternative embodiments, the plug may comprise a metal or other material and may include one or more resilient annular seals along its outer periphery to couple to the filter element.

In order to allow pressure to be applied to the filter element 22, the plug preferably includes an inner aperture and a connector 116 for connecting the plug to the pressure line 104. The pressure line 104 comprises a conduit capable of communicating gas flow, e.g., air flow, to or from the interior of the filter element 22. The pressure line 104 is preferably flexible to facilitate movement of the probe 100 between filter elements. The pressure line 104 preferably includes a regulating valve 118 for regulating pressure in the pressure line and an indicator valve 120 for providing a visual indication of the pressure. In order to apply pressure to the filter element 22, the pressure line may be coupled to a pressure control arrangement, for example, as shown in Figure 2. In an alternative embodiment, the regulating valve and the pressure indicator may be included in the pressure control arrangement to which the pressure line is coupled.

The microphone M4 may comprise any of the microphones previously

described that are capable of locating defective filter elements based on sounds emanating from defective filter elements. In the illustrated embodiment, the microphone M4 is coupled to an elongate member 122 to allow the microphone M4 to extend into the core of the filter element. A coupling device 124, such as one or more electrical or optical connectors transmits output signals from the microphone to the processing circuit. In an alternative embodiment, a plurality of microphones may be coupled to the plug M4.

In operation, the probe 100 may be used to determine the specific location of defective filter elements in combination with the device of Figure 2. For example, according to one test, the device of Figure 2 may identify a region or a subgroup of filter elements in a filter assembly suspected of containing one or more defective filter elements. The filter elements of interest may be wetted with a wetting solution or with the filtrate. If the filter elements were previously tested using a device similar to the device of Figure 2 where the downstream region 28 was partially filled with liquid, the downstream region may be pressurized to drive the liquid from the filter cores to the upstream region 26. The cores of the filter elements suspected of being defective are preferably substantially free from liquid. In one exemplary test, the liquid may be retained in the upstream region 26 and utilized to both wet the filter elements and provide a medium for bubbles to form. In another test, the liquid may be drained from the upstream region 26 after being forced from the downstream region 28 through the filter elements, provided that the filter elements isolated for testing remain wetted. Depending on the number of filter elements isolated for testing, and the duration of each test, it may be desirable to re-wet some of the filter elements.

Once the filter elements isolated for testing are wetted, the probe 100 is inserted into the open end cap 106 of one of the filter elements suspected of being defective. The plug 102 preferably forms a sealing arrangement with the end cap 106 of the filter element 22. The pressure control apparatus coupled to the pressure line

104 increases the pressure in the core of the filter element 22. Alternatively, the pressure control arrangement may decrease the pressure in the core of the filter element by creating a vacuum, e.g., negative pressure, in the core of the filter element. The microphone monitors sounds in the core of the filter element. If the microphone detects a sound indicative of a defect, e.g., gas passing through an oversized pore in the filter element, the processing circuit preferably indicates to the operator that the filter element is defective. If the filter element passes the test, the operator preferably inserts the probe into another filter suspected of being defective and repeats the test. In this manner, the probe 100 is used in combination with the device of Figure 2 to determine the specific locations of defective filter elements. In an alternative embodiment, the probe may be used without the device of Figure 2 to individually test and locate defective filter elements. However, using the probe in combination with the device of Figure 2 is preferred, since the device of Figure 2 reduces the number of filter elements to be tested using the probe 100.

In still another alternative embodiment, the probe may be configured to apply pressure to filter elements suspected of being defective and a microphone or microphones for monitoring sounds emanating from defective filter elements may be separate from the probe. Referring to Figure 9, the probe 100a includes a plug 102a, an aperture 114, and a connector 116. The plug 102a is couplable to a filter element to allow pressure to be applied to the filter element, as previously described. During testing, the aperture 114 and the connector 116 are connected to a pressure line 104. The pressure line 104 is connected to a pressure control arrangement.

The probe 100a may be used in combination with a device similar to the device of Figure 2 in any manner to locate defective filter elements. In order to listen for bubbles or gas in the upstream region of the filter assembly, the device in Figure 2 may be modified to include microphones in both the upstream and downstream regions. In one test, locations of defective filter elements may be verified based on the formation of bubbles in the upstream region caused by defects.

In another test, the locations of defective filter elements can be verified based on the bursting of bubbles caused by defects. In yet another test, the locations of defective filter elements can be verified based on sounds caused by gas passing through a defect.

In any of these tests, the device similar to the device of Figure 2 with microphones in both the upstream and downstream regions preferably identifies one or more filter elements likely to be defective, as previously described. Next, the housing may be opened, and the cores of the filter elements may be drained. The upstream region of the filter assembly may then be either partially or completely filled with water, depending on the configuration of the filter elements and the desired method for testing the filter elements. For example, if the filter elements 22 of the filter assembly 8 each include a filter medium that extends completely to the tube sheet 24, then the upstream region is preferably filled completely with water so that the entire filter medium of each of the filter elements is submerged. If the filter medium of each of the filter elements does not extend completely into the tube sheet 24, the upstream region of the filter housing may be partially filled with a liquid. For example, the filter elements may include end caps that extend below the tube sheet 24. In such a case, the filter medium of each of the filter elements may be completely submerged without filling the entire upstream region of the filter assembly.

Partially filling the upstream region with water leaves an air gap between the surface of the liquid and the underside of the tube sheet 24, thereby allowing bubbles to burst. The bursting of bubbles may be used to locate defective filter elements. If the upstream region of the filter assembly is filled with liquid, i.e., up to the level of the tube sheet 24, there is no gas-liquid interface to allow bubbles to burst. Accordingly, if the upstream region is filled with liquid, the formation of bubbles is preferably used to locate defective filter elements. If the upstream region is only partially filled, either the formation or bursting of bubbles may be used to locate

defective filter elements. Thus, whether or not to partially of fully fill the upstream region of the housing depends both on the configuration of the filter elements and the desired test method.

In order to locate defective filter elements using the probe 100a, one or more microphones are preferably located in the upstream region of the filter assembly. If the upstream region is completely filled with liquid, then the microphone is preferably located in the liquid to monitor the formation of bubbles. If the upstream region is partially filled, the microphone may be located either in the liquid or in the region between the surface of the liquid and the tube sheet. For example, the microphone may be mounted to the filter housing or to the underside of the tube sheet.

The microphone is preferably coupled to the processing circuit 2. The plug 100a is coupled to one of the filter elements suspected of being defective. The pressure control arrangement 6 increases the pressure in the filter element under test. The microphone M5 monitors the sounds emanating from the filter element under test. For example, if the microphone is in the liquid and the upstream region of the filter assembly is completely filled with water, the microphone preferably detects the formation of bubbles in the liquid. The processing circuit verifies the presence of the defective filter element based on the formation of bubbles. If the microphone is in the liquid and the upstream region is partially filled, the microphone may detect both the formation and bursting of bubbles. Thus, in such an embodiment, the processing circuit may verify the presence of the defective filter element based on either the formation or bursting of bubbles. If the upstream region is partially filled and the microphone is in the region between the liquid and the tube sheet, the acoustic signals caused by the bursting of bubbles are likely to be stronger than those caused by the formation. Accordingly, the processing circuit preferably utilizes the bursting of bubbles to verify the presence of the defective filter element.

If no bubbles form or burst, the processing circuit determines the filter element under test to be non-defective. The operator moves the plug to another filter

element suspected of being defective and repeats the test. In this manner, the probe 100a of Figure 9 may be used in combination with the device of Figure 2 to locate defective filter elements based on either the formation or bursting of bubbles.

The above described embodiments of the present invention illustrates a method for locating a defective filter element based on bubbles rising in a liquid and collapsing at the surface of the liquid above a defective filter element. Because the bubbles burst above the defective filter element, the problem of locating the defective filter element is two-dimensional, based on the lateral, e.g., radial, location of the bubbles. However, the present invention is not limited to such a method. For example, in an alternative embodiment, the filter elements may be wetted without filling the cores of the filters with liquid. Sounds caused by defects may not originate at the same longitudinal, e.g., axial, location. Thus, the problem of locating the defective filter element may be three-dimensional. In the three-dimensional case, an algorithm similar to that illustrated for the two dimensional case may be used. For example, the curves H_0-H_n and I_0-I_n in Figures 4 and 5 become surfaces of rotation about the axis between the foci. Each of the resulting surfaces is a hyperboloid representing a locus of points where the difference in the distances between the points on the surface and the microphones is constant. The intersection of two or more of these surfaces represents sets of potential locations of a defective filter element. Thus, in the three dimensional case, it may be preferable to compute more than two sets of potential locations, since the intersection of two sets may not yield a single point.

In other embodiments of the present invention, the problem of locating defective filter elements may be one-dimensional. For example, where arrays of filter elements are long in comparison with the width of a filter housing, two microphones may be placed at opposite ends of the array of filter elements. The filter elements may be wetted and pressurized. The microphones may detect sounds emanating from defective filter elements at different times and/or intensity levels.

The processing circuit may locate defective filter elements using the algorithm described above for the two-dimensional case or using any one-dimensional algorithm, for example, any algorithm used in ultrasonic leak detection in pipes. In alternative embodiments, one or more microphones may be movable or a plurality of microphones may be axially spaced to determine the one-dimensional locations of defective filter elements.

Although the embodiments illustrated in Figures 2 and 2a depict a device for locating defective filter elements in a single filter assembly, the present invention is not limited to such an embodiment. For example, a filtration system may include a plurality of filter assemblies, each including a filter housing an a plurality of filter elements. In such a filtration system, an embodiment of the present invention may include a sound monitoring apparatus coupled to each of the filter assemblies to locate defective filter elements. A pressure control arrangement may also be coupled to each of the filter assemblies. A processing circuit may receive output signals from the sound monitoring apparatuses to locate defective filter elements in each filter assembly being tested. Thus, according to some embodiments of the present invention, a plurality of filter assemblies can be tested in parallel, thereby reducing the amount of labor and hardware involved in testing.

Although the above-described method for locating defective filter elements is based on the relative time of arrival of acoustic signals at a plurality of microphones, the present invention is not limited to such a method. For example, the relative intensities of acoustic signals detected by a plurality of microphones may be used to locate defective filter elements. In such an embodiment, the processing circuit may utilize any appropriate geometric algorithm to locate defective filter elements. For example, one or more directional microphones may be used to locate defective filter elements in a filter assembly. The directional microphones may detect a beam of sound representing the direction from which the sound intensity caused by a defect is maximized. Based on these directions, the processing circuit may determine the

locations of defective filter elements.

Although the above illustrated methods for locating defective filter elements describe increasing the pressure in one region of a filter housing to draw gas into another region, the present invention is not limited to increasing pressure. For example, in embodiments in which the filter elements are wetted with a wetting solution and both regions of the filter housing are filled with a gas, the pressure may be decreased in one of the regions to draw air through a defect into that region. Any method for producing a pressure differential across a filter element to produce sounds indicative of defects is within the scope of the invention.

Any of the above-described methods or tests for locating defective filter elements may be used in combination with a variety of tests, for example, a pressure hold test, to determine whether any of the filter elements are defective. Once one or more filter elements are determined to be defective using a pressure hold test, the defective filter elements may be located using any of the methods described above.

As stated above, the methods and systems for locating defective filter elements according to the present invention may be used to located defective filter elements in any type of filter housing including a plurality of filter elements, such as a stacked filter assembly. The term "stacked filter assembly" includes any filter assembly where a plurality of filter elements are axially arranged vertically, horizontally, or at any angle between vertical and horizontal along a conduit, such as a permeate conduit. The term also includes filter assemblies including a plurality of modular stacks of filter elements arranged, for example, in receptacles that are detachably coupled to each other to form a filter assembly. In such filter assemblies, the embodiments of the present invention may be used to locate a stack or module containing a defective filter element or a defective filter element within a stack.

Referring to Figure 10, a stacked filter assembly 200 includes a plurality of receptacles 202 detachably connected to each other. Each of the receptacles 202 may be separable into first and second portions 204 and 206. Each receptacle 202 houses

a stack 208 of filter elements 210. The stack may also include a plurality of spacers 212. Each filter element 210 may be sandwiched between a pair of the spacers 212. The filter elements 210 and the spacers 212 may be of any geometry, e.g., circular, rectangular, or any other shape suitable for filtering liquids. The filter elements 210 and the spacers 212 are axially arranged along a conduit 214. Each of the conduits 214 is perpendicularly oriented with respect to the axis of the filter assembly 200. Thus, the filter elements 210 are parallel to the axis of the filter assembly 200. High pressure fluid flows through a flow channel 216 of the filter assembly. Some of the fluid, i.e., the permeate, flows through each stack 208 to a permeate outlet 218 and exits the filter assembly 200. One of many examples of a stacked filter assembly is disclosed in United States Patent 5,626,752, the disclosure of which is incorporated herein by reference.

Because the filter assembly 200 may include a plurality of receptacles, it may be desirable to identify a receptacle containing one or more defective filter elements. Accordingly, one or more microphones may be placed at any location inside the housing of the filter assembly 200. For example, a microphone 300 may be located in the flow channel 216. Although not illustrated in Figure 10, the microphone 300 may also be coupled to a processing circuit similar to the processing circuit in Figure 2. The flow channel 216 may be filled with a liquid. A liquid level control device, such as a valve or a pump coupled to a liquid source or a drain may be coupled to the processing circuit to control the liquid level in the filter assembly 200. Pressure, e.g., gas pressure, may be applied to the filter elements in any manner. For example, pressure may be applied through the permeate outlet 218. A pressure control arrangement similar to that describe with respect to Figure 2 may be utilized to apply pressure to the filter elements. Bubbles caused by a defective filter element may form in the flow channel 216 and the sound of the bubbles popping at or rising to the surface of the liquid may be detected. If the filter assembly 200 is vertically oriented, the stacks of filter elements will be located vertically with respect to each

other. The liquid level inside the flow channel 216 can be decreased until the bubbles cease to form and the sound of popping or rising is no longer detected. When the bubbles cease to form, the filter elements located near the level of the liquid may have a defect. Alternatively, the liquid level inside the flow channel can be initially zero and gradually increased until the water level reaches a defect, causing bubbles to form. The sound of bubbles popping at or rising to the surface of the liquid may then be detected. Again, the filter element near the level of the liquid may have a defect. The processing circuit may indicate the liquid level and/or the location of the defective filter element to an operator when the bubbles cease to form. Alternatively, the processing circuit may indicate the presence or absence of sounds caused by the bubbles and the defective filter element may be located visually by observing the liquid level when the sounds cease.

If the filter assembly 200 is horizontally oriented, so that the filter stacks are horizontally located with respect to each other, defective stacks 208 or filter elements 210 may be located with a plurality of microphones preferably located inside the housing of filter assembly 200 using a method similar to that described with respect to the embodiment of Figure 2. In another alternative, a single microphone may be associated with each stack of filter elements to monitor sounds caused by defects in each stack.

In an alternative operating environment for embodiments of the invention, the filter elements 210 of the filter assembly 200 illustrated in Figure 10 may be oriented perpendicularly with respect to the axis of the filter housing. In such an operating environment, one or more microphones may be located inside the filter housing. The filter housing may be filled with a liquid. Pressure may be applied to the filter elements through apertures in the conduits of each stack, forming bubbles in the housing. If the filter housing is vertically oriented, the filter elements will be horizontally oriented. Thus, the liquid level inside the housing can be varied until the formation of bubbles ceases and the sound of popping or rising bubbles ceases,

identifying a defective filter element or a stack containing a defective filter element at or near the liquid level. Alternatively, the liquid level inside the housing can be initially zero and gradually increased until bubbles begin to form and the sound of rising or popping bubbles is detected.

If the filter housing is horizontally oriented, the filter elements will be vertically oriented, and defective stacks and/or filter elements can be located using one or more microphones positioned at various locations inside the housing in a method similar to that described with respect to Figure 2. Alternatively, a single microphone may be positioned near each stack or module of filter elements to monitor sounds caused by defects in each stack.

The present invention is not limited to locating defective filter elements or modules in the filter assembly illustrated in Figure 10. For example, the above-described methods of varying the liquid level and monitoring bubble sounds may be used to locate defective filter elements or modules in any type of filter assembly including vertically-extending arrays of horizontally-oriented filter elements. In addition, the method of determining the location of bubbles bursting at the surface of a liquid described with respect to Figure 2 may be used to locate defective filter elements or modules in any filter assembly including horizontally-extending arrays of vertically-oriented filter elements.

Further, the present invention is not limited to using passive listening techniques or monitoring bubbles bursting at the surface of a liquid to locate defective filter elements. For example, in an alternative embodiment, an active sonar system may be used to locate defective filter elements. In an active sonar system, one or more sound transducers may be located inside of a filter housing. For example, in the embodiment illustrated in Figure 2, a sound transducer may be located on the upstream side 26 of the plurality of filter elements 22. One or more microphones may also be located on the upstream side 26 of the filter elements 22. Alternatively, the sound transducer may be used to both emit and record sounds. The upstream

region 26 may be partially or completely filled with a liquid to allow the production of bubbles.

In order to obtain a benchmark of the acoustic characteristics of the filter assembly when no defects are present, it may be desirable to emit a pulse of acoustic energy into the chamber and measure the response before the filter elements are pressurized. Once the benchmark measurement is obtained, the downstream region 28 may be pressurized. Bubbles may originate from a defect in one of the filter elements 22. The sound transducer may emit a pulse of acoustic energy into the downstream region 26. The microphones and/or the sound transducer may measure the resultant acoustic energy in the filter assembly. The bubbles may affect the acoustic energy received, e.g., through reflections or refractions. The source of the bubbles may be located based on the measured acoustic energy, the benchmark measurement, and/or the speed of sound in the liquid. Processing algorithms similar to those used in echo ranging active sonar systems may be used to locate a defective filter element. For example, the processing algorithms may be used to obtain a bearing of a bubble stream originating from a defect. The speed of sound in the liquid may then be used to locate the defective filter element along the bearing.

The present invention is not limited to emitting pulses of acoustic energy in order to locate defective filter elements. For example, in an alternative arrangement, acoustic energy may be continuously emitted and monitored. Bubbles rising from defective filter elements may alter the measured energy. The changes in received energy may be used to locate defective filter elements.

While the invention has been described in some detail by way of illustration and example, it should be understood that the invention is susceptible to various modifications and alternative forms, and is not restricted to the specific embodiments set forth. It should be understood that these specific embodiments are not intended to limit the invention but, on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention.

What is claimed is:

1. A device for locating defective filter elements among a plurality of filter elements comprising:

a sound monitoring apparatus associated with a plurality of filter elements to detect sounds caused by one or more defects in the plurality of filter elements and produce output signals indicative of the sounds; and

a processing circuit coupled to the sound monitoring apparatus to determine the location of defective filter elements among the plurality of filter elements based on the output signals.

2. A filter assembly comprising:

a housing;

a plurality of filter elements located in the housing;

a sound monitoring apparatus associated with the filter elements to detect sounds caused by one or more defects in the filter elements; and

a processing circuit coupled to the sound monitoring apparatus to determine the location of defective filter elements based on the output signals.

3. A probe for locating defective filter elements among a plurality of filter elements comprising:

a plug removably couplable to a filter element to allow a predetermined pressure to be applied to the filter element;

a microphone cooperatively arranged with the plug to detect sounds indicative of a defect in the filter element; and

a processing circuit coupled to the microphone to indicate defective filter elements based on the sounds.

4. A method for locating a defective filter element among a plurality of filter elements comprising;

forcing gas through defective filter elements among a plurality of filter elements;

detecting sounds caused by the gas; and

determining the location of a defective filter element based on the sounds.

5. A method for locating defective filter stacks or elements among a plurality of filter stacks or elements comprising:

controlling a liquid level inside a filter housing with respect to a plurality of filter stacks or filter elements;

applying gas pressure to the filter stacks or the filter elements;

monitoring sounds caused by bubbles originating from defective filter stacks or filter elements; and

locating a defective filter stack or filter element based on the sounds.

6. The method of claim 5 wherein locating a defective filter stack or filter element comprises:

reducing the liquid level inside the filter housing until the bubbles originating from the defect cease to form; and

identifying a defective filter stack or filter element based on the reduced liquid level.

7. The method of claim 5 wherein locating a defective filter stack or filter element comprises:

increasing the liquid level inside the filter housing until bubbles originating from the defect begin to form; and

locating a defective filter element based on the increased liquid level.

8. A method for locating defective filter elements comprising:

transmitting acoustic energy within a filter housing;

monitoring acoustic energy reflected or transmitted within the housing; and

locating defective filter elements based on the monitored acoustic energy.

9. The method of claim 8 comprising:

partially or completely filling a first region inside the filter housing with a liquid; and

pressurizing a second region inside the filter housing to force gas through defective filter elements and form bubbles in the second region, wherein locating defective filter elements includes analyzing acoustic energy transmitted through or reflected from the bubbles.

10. A system for locating a defective filter element among a plurality of filter elements comprising;

a pressure control arrangement associated with a filter housing for forcing gas through defective filter elements among a plurality of filter elements inside the filter housing;

at least one sound monitoring apparatus associated with the filter housing for detecting sounds caused by the gas; and

a processing circuit coupled to the sound monitoring apparatus for determining the location of a defective filter element based on the sounds.

11. A system for locating defective filter stacks or elements among a plurality of filter stacks or elements comprising:

a liquid level control device associated with a filter housing for controlling a liquid level inside a filter housing with respect to a plurality of filter stacks or filter elements;

a pressure control arrangement associated with the filter housing for applying gas pressure to the filter stacks or the filter elements;

a sound monitoring apparatus associated with the filter housing for monitoring sounds caused by bubbles originating from defective filter stacks or filter elements; and

a processing circuit coupled to the sound monitoring apparatus for indicating the presence or absence of sounds caused by the bubbles.

12. The system of claim 11 wherein the liquid level control device reduces the liquid level inside the filter housing until the processing circuit indicates the absence of bubbles originating from a defect.

13. The system of claim 12 wherein the processing circuit locates a defective filter stack or element based on the liquid level when the sounds from the bubbles cease.

14. The system of claim 11 wherein the liquid level control device reduces the liquid level until the processing circuit indicates the presence of bubbles originating from a defect.

15. The system of claim 14 wherein the processing circuit locates a defective filter stack or element based on the liquid level when the sounds from the bubbles begin.

16. A system for locating defective filter elements comprising:

a transducer for transmitting acoustic energy within a filter housing;

at least one sound monitoring apparatus for monitoring acoustic energy reflected or transmitted within the housing; and

a processing circuit coupled to the sound monitoring apparatus and the sound

transducer for locating defective filter elements based on the monitored acoustic energy.

17. The system of claim 16 further comprising:

a liquid level control device for partially or completely filling a first region inside the filter housing with a liquid; and

a pressure control arrangement for pressurizing a second region inside the filter housing to force gas through defective filter elements and form bubbles in the second region, wherein locating defective filter elements includes analyzing acoustic energy transmitted through or reflected from the bubbles.

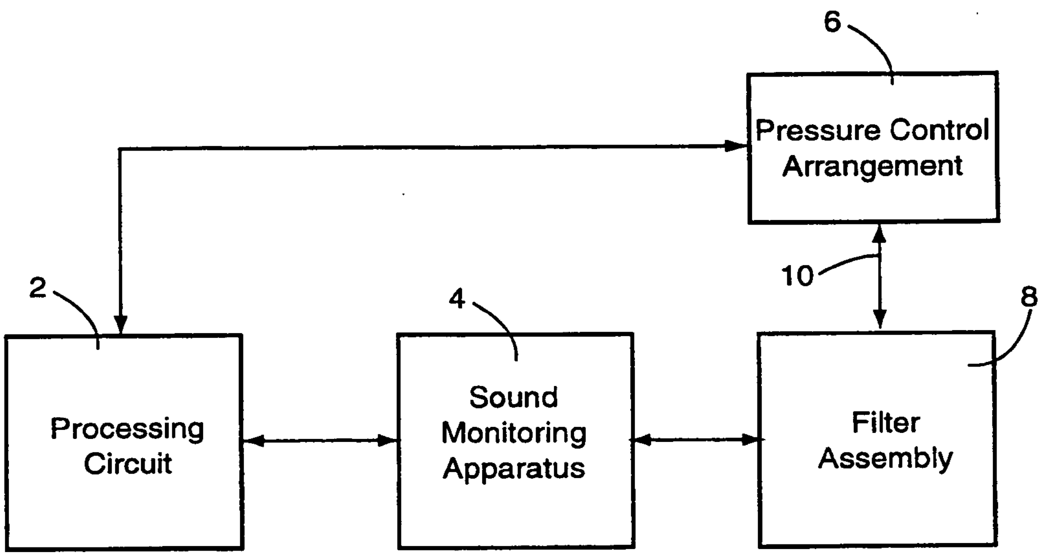
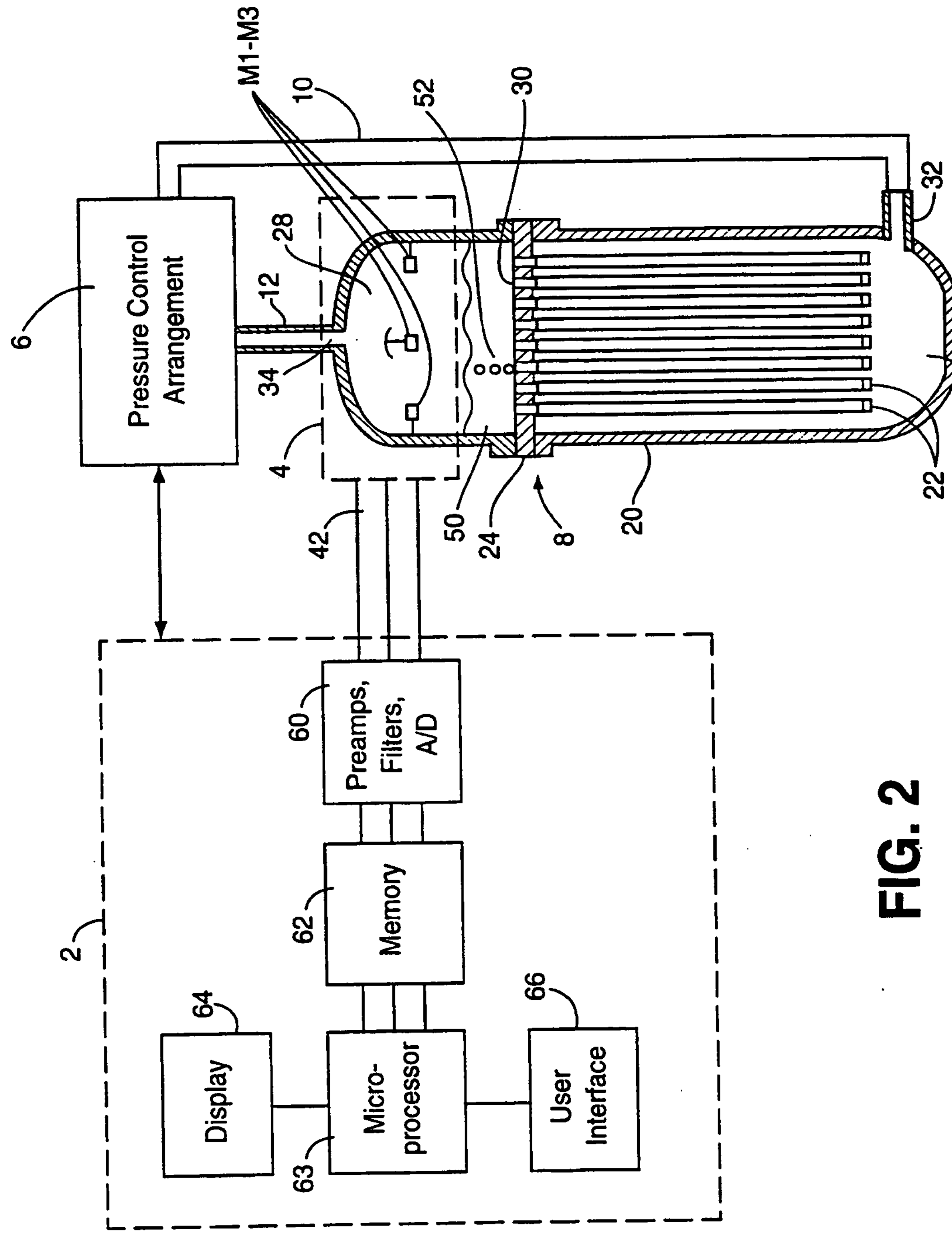

6
Pressure Control Arrangement
10
2
4
8
Processing Circuit
Sound Monitoring Apparatus
Filter Assembly

FIG. 1


Pressure Control Arrangement
Preamps, Filters, A/D
Memory
Display
Micro-processor
User Interface
M1-M3
2
4
6
8
10
12
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22
24
26
28
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34
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52
60
62
63
64
66

FIG. 2

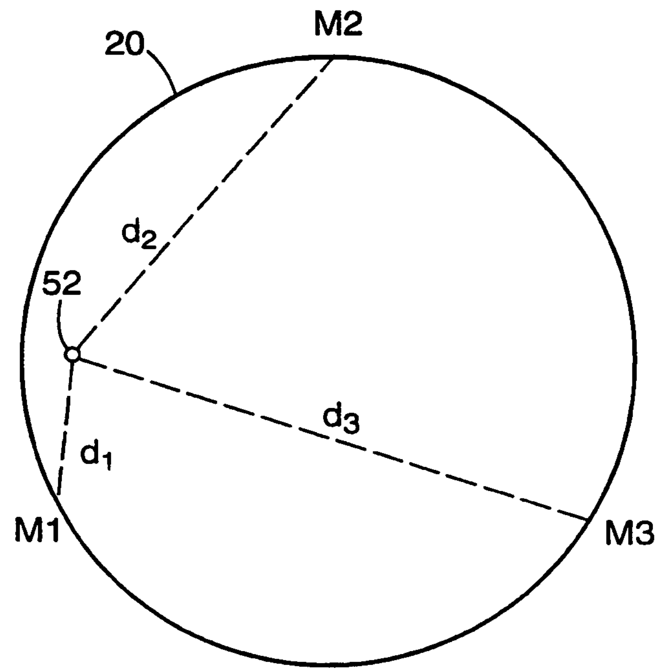


FIG. 2a

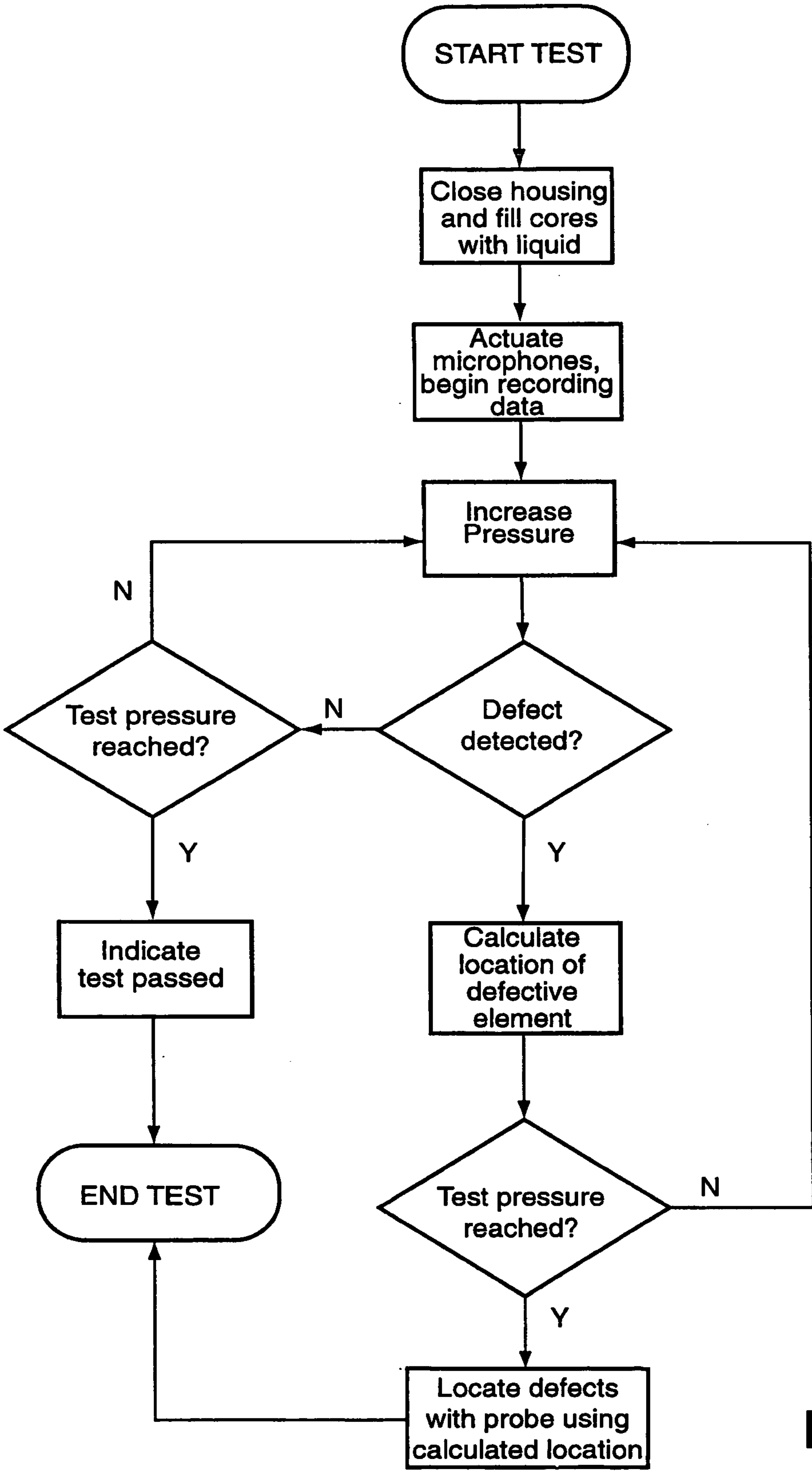
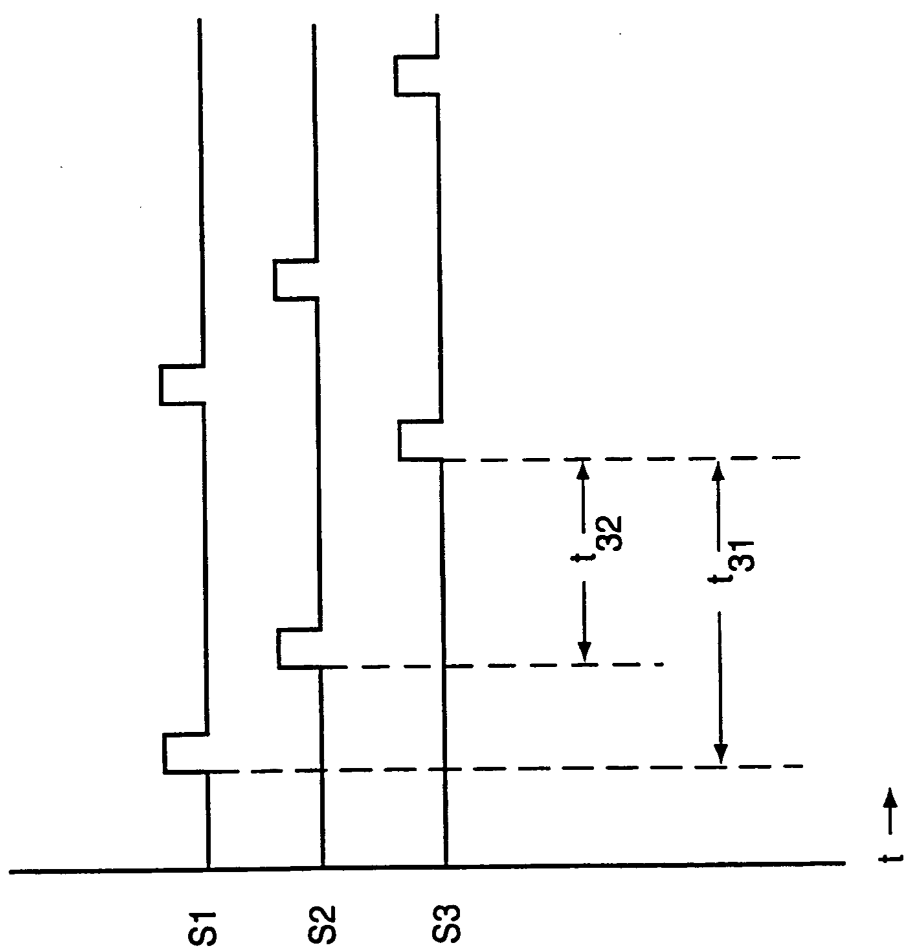

START TEST
Close housing and fill cores with liquid
Actuate microphones, begin recording data
Increase Pressure
N
Test pressure reached?
N
Defect detected?
Y
Y
Indicate test passed
Calculate location of defective element
END TEST
Test pressure reached?
N
Y
Locate defects with probe using calculated location

FIG. 3

FIG. 3a FIG. 3b FIG. 3c



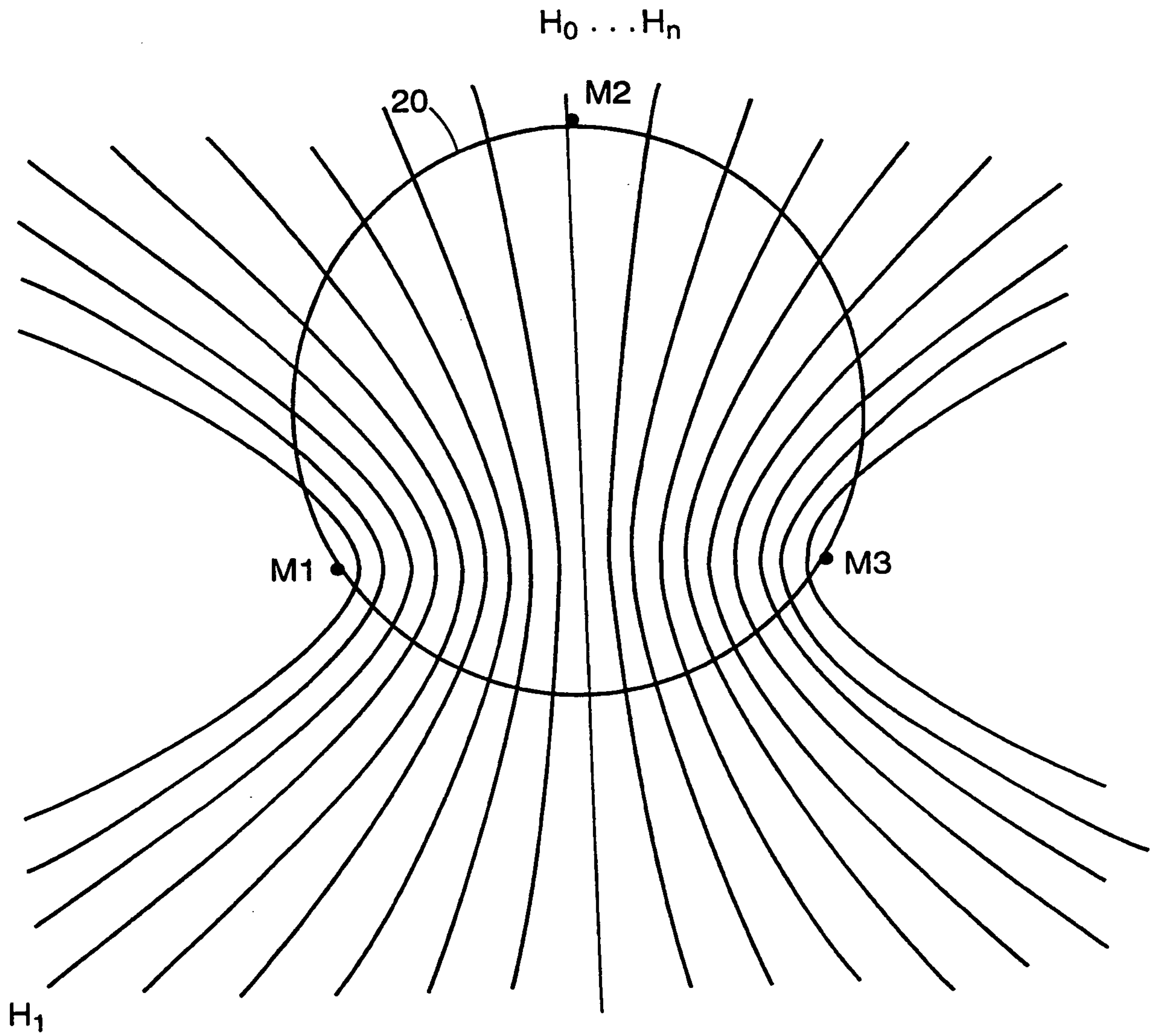


FIG. 4

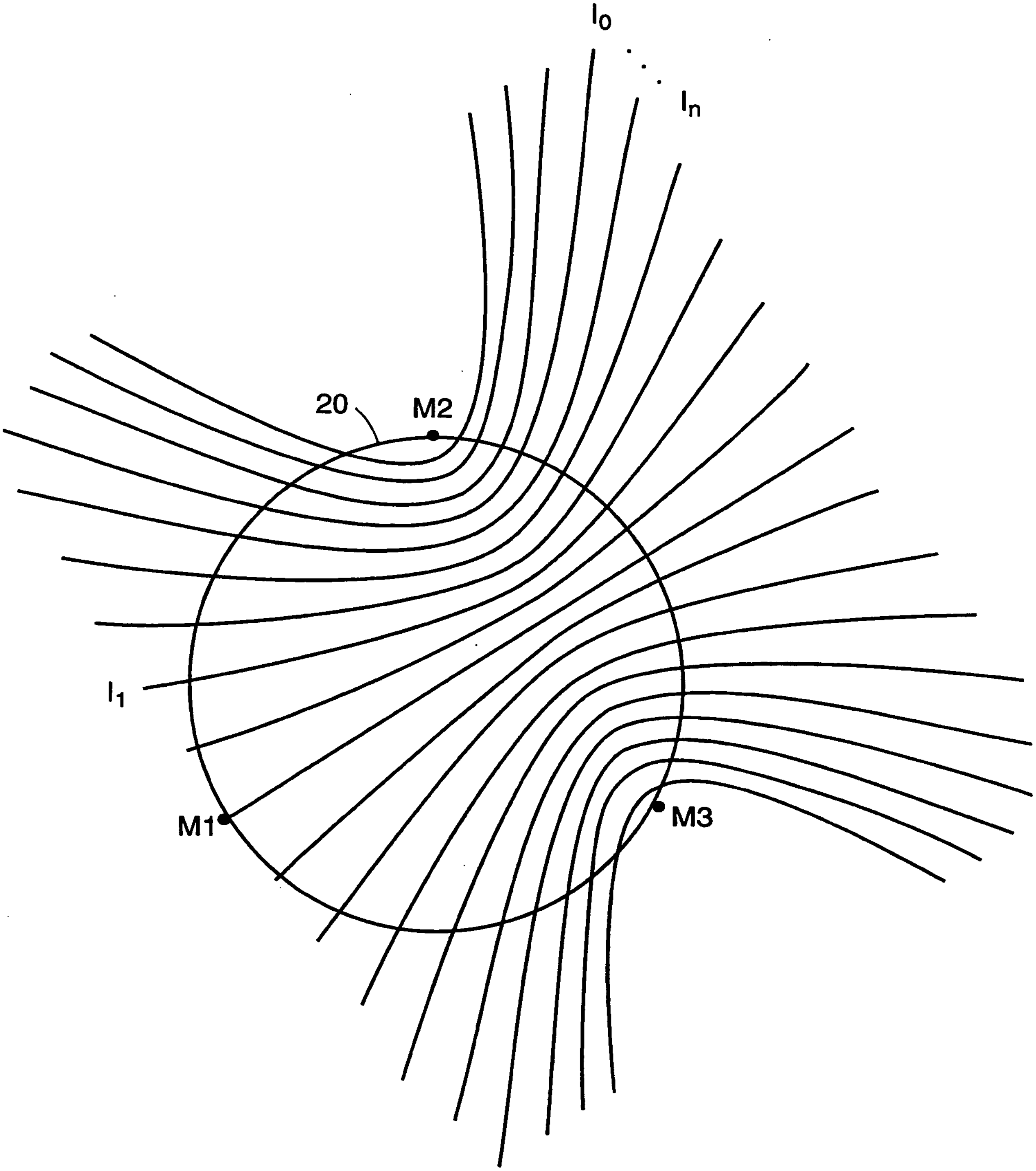


FIG. 5

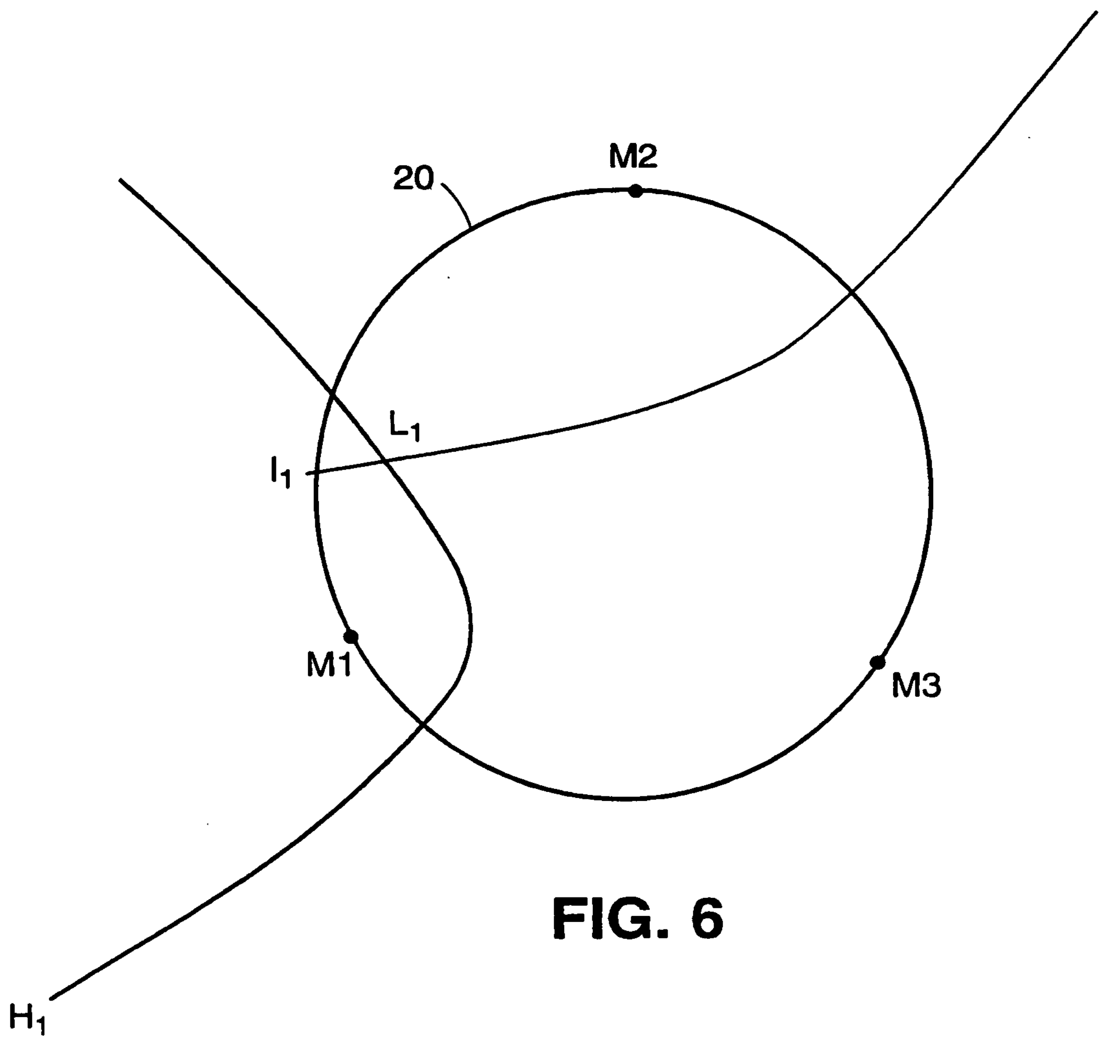


FIG. 6

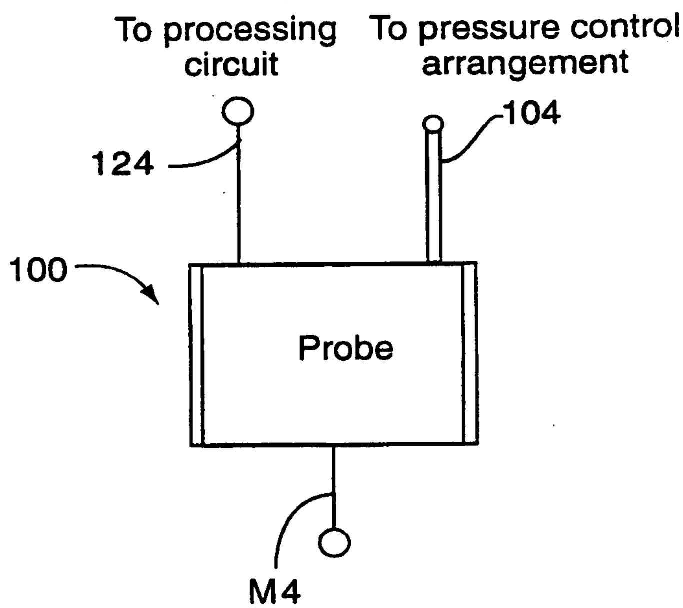

To processing circuit
To pressure control arrangement
104
124
100
Probe
M4

FIG. 7

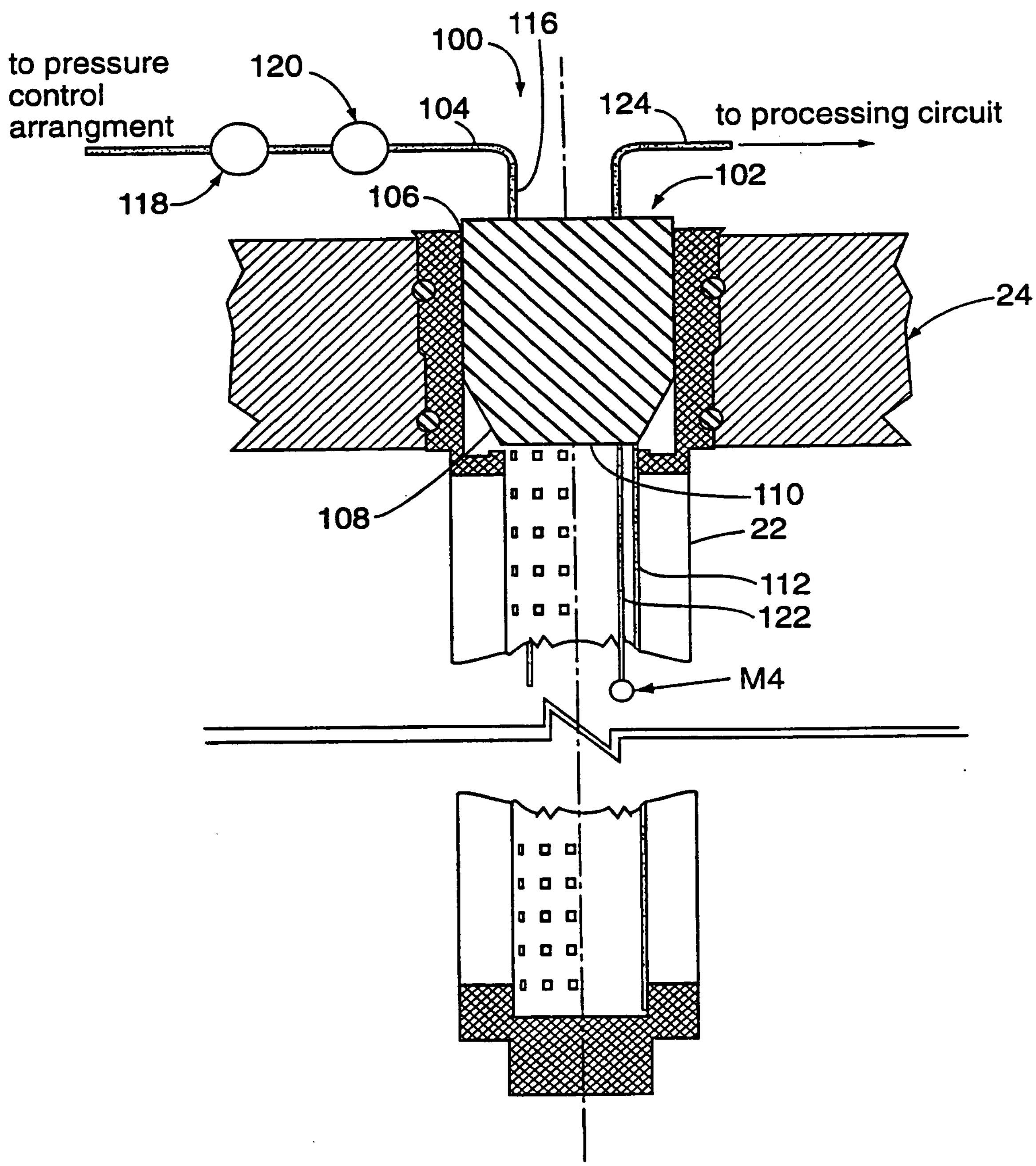

to pressure control arrangment
120
100
116
104
124
to processing circuit
102
118
106
24
110
108
22
112
122
M4

FIG. 8

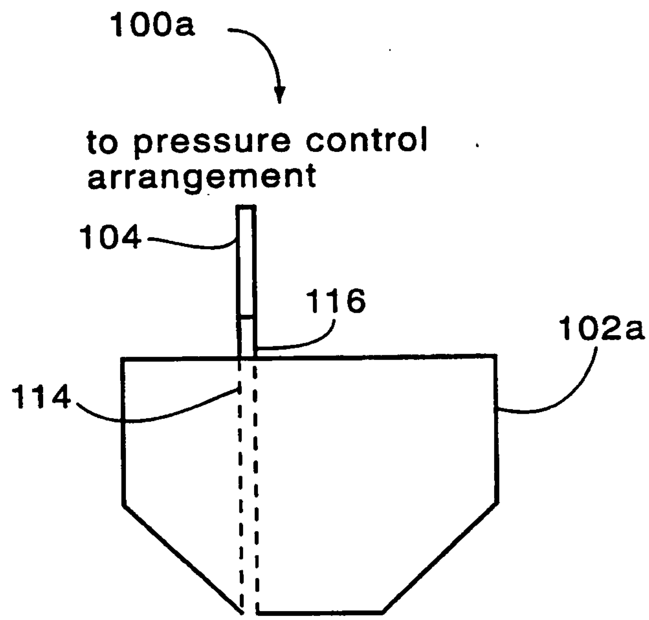


FIG. 9

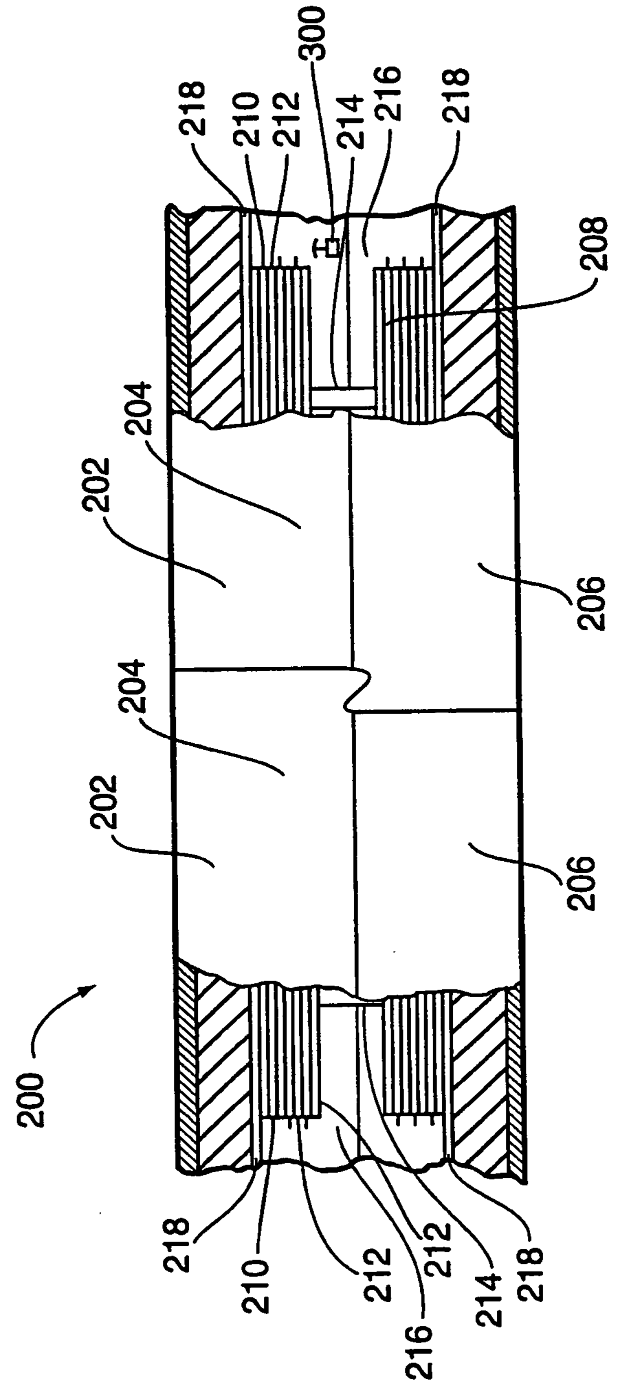

300
218
210
212
214
216
218
208
204
202
206
204
202
206
200
218
210
212
216
212
214
218

FIG. 10

INTERNATIONAL SEARCH REPORT

In ational Application No
PCT/US 98/20357

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B01D65/10 B01D46/24 G01N15/08 G01S5/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B01D G01N G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 94 11721 A (PALL CORP ;HOPKINS SCOTT D (US); SPENCER DANIEL W (US); LIPARI CHA) 26 May 1994 see abstract see page 12, line 32-34 see page 52, line 11-26	1-17
X	WO 95 32412 A (PALL CORP ;HOPKINS SCOTT D (US); SPENCER DANIEL W (US); LIPARI CHA) 30 November 1995 see abstract see page 10, line 7-8 see page 35, line 27 - page 36, line 3	1-17
A	US 4 744 240 A (REICHELT GERT) 17 May 1988 see abstract	1-17

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 February 1999	17/02/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hoffmann, A

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PCT/US 98/20357

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A	PATENT ABSTRACTS OF JAPAN vol. 009, no. 257 (P-396), 15 October 1985 & JP 60 107581 A (MATSUSHITA DENKI SANGYO KK), 13 June 1985 see abstract ---	1-17
A	EP 0 583 558 A (BABCOCK ENERGIE UMWELT) 23 February 1994 see the whole document ---	1-17
A	WO 96 24037 A (GORE & ASS) 8 August 1996 see the whole document -----	1-17

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Information on patent family members

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